

KTeV Results: $K_L \rightarrow p^0 \ell\bar{\ell}$ ($\ell = e, m, n$)

Brookhaven Workshop on Future Kaon Experiments

May 13, 2004

Julie Whitmore, Fermilab

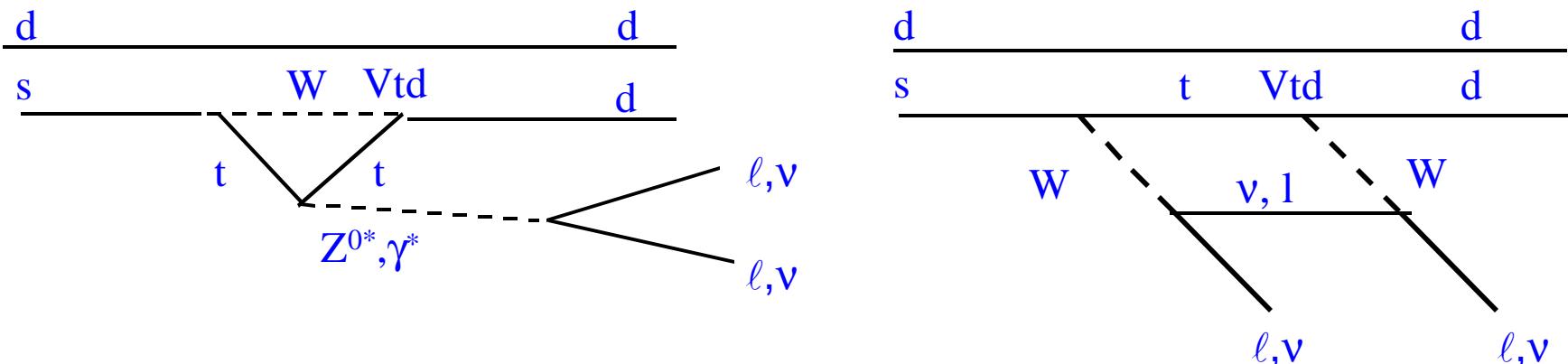
- Physics Motivation - Direct CP Violation
- KTeV Detector
- Results
- Summary

The KTeV Collaboration:

Arizona, Campinas, Chicago, Colorado, Elmhurst, Fermilab, Osaka,
Rice, Rutgers, Sao Paulo, UCLA, UCSD, Virginia, Wisconsin

Direct CP Violation in $K_L \xrightarrow{R} p^0 \bar{\ell}\ell$

Direct ($K_L \mu K_2 + e K_1; K_2 \xrightarrow{R} p^0 g^ p^0 Z^*$)*



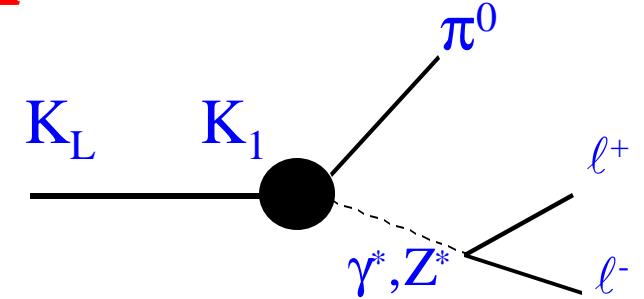
Theoretical Predictions

The Golden Mode

$$BR_{DIR} (K_L \rightarrow p^0 n \bar{n}) = \left(\frac{m_t}{m_W} \right)^{2.2} A^{-4} h^2 \sim (2.6 \pm 1.2) \times 10^{-11}$$

CP Violation in $K_L \xrightarrow{\textcircled{R}} p^0 \ell\bar{\ell}$

CPV = Indirect ($K_L \mu K_2 + e K_1$; $K_1 \rightarrow p^\rho g^* p^0 Z^*$) + Interference + Direct ($K_L \mu K_2 + e K_1$; $K_2 \xrightarrow{\textcircled{R}} p^\rho g^* p^0 Z^*$)



Theoretical Predictions

(from theory + BR($K_s \rightarrow \pi^0 \ell\bar{\ell}$) (NA48))

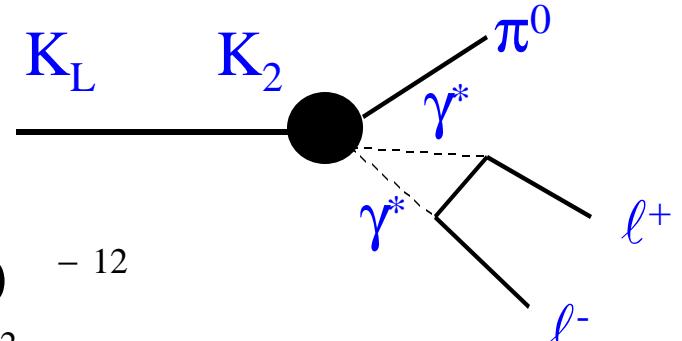
$$\begin{aligned} BR \quad (K_L \rightarrow p^0 ee)_{CPV} &\sim (17 \pm 9 + 5) \times 10^{-12} \\ BR \quad (K_L \rightarrow p^0 mm)_{CPV} &\sim (9 \pm 6 + 1) \times 10^{-12} \end{aligned}$$

Conserving ($K_L \mu K_2 + e K_1$; $K_2 \rightarrow p^\rho g^* g^*$)

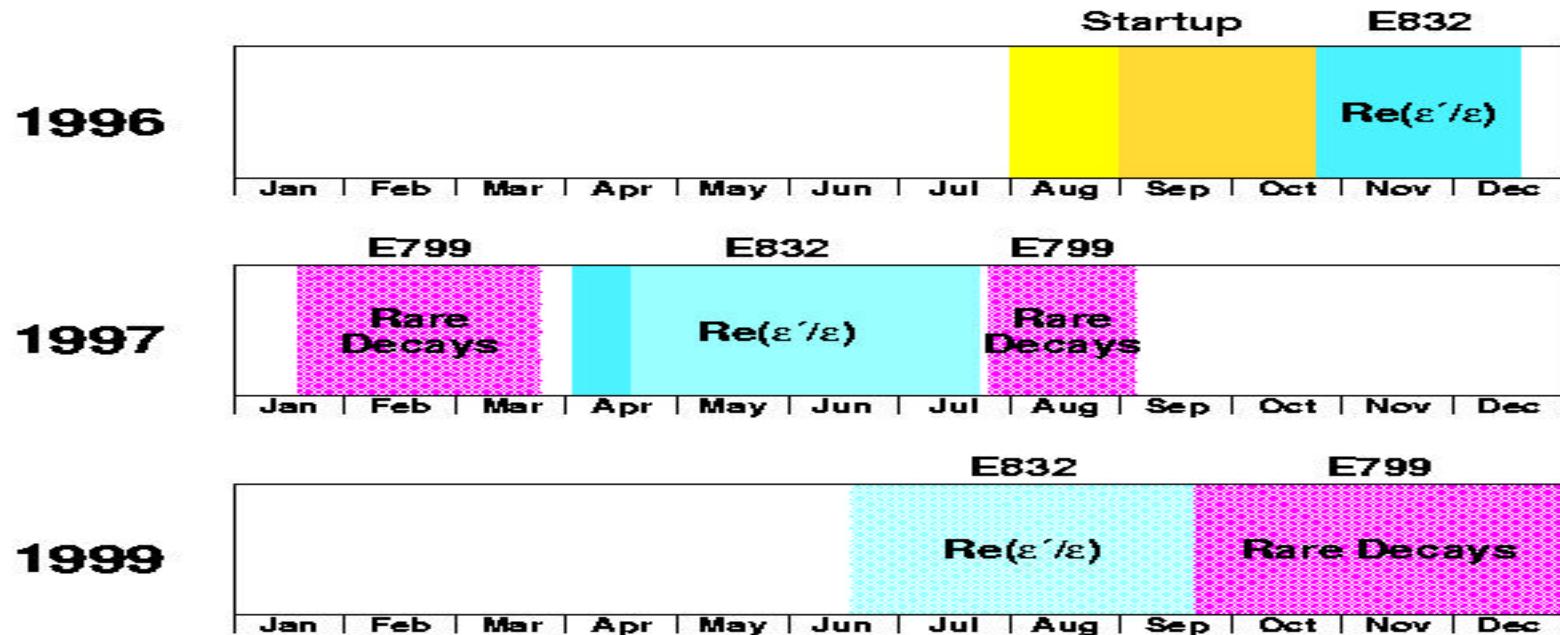
Theoretical Predictions

(from theory + BR($K_s \rightarrow \pi^0 \gamma\gamma$))

$$\begin{aligned} BR \quad (K_L \rightarrow p^0 ee)_{CPC} &\sim 0.5 \times 10^{-12} \\ BR \quad (K_L \rightarrow p^0 mm)_{CPC} &\sim 5 \times 10^{-12} \end{aligned}$$

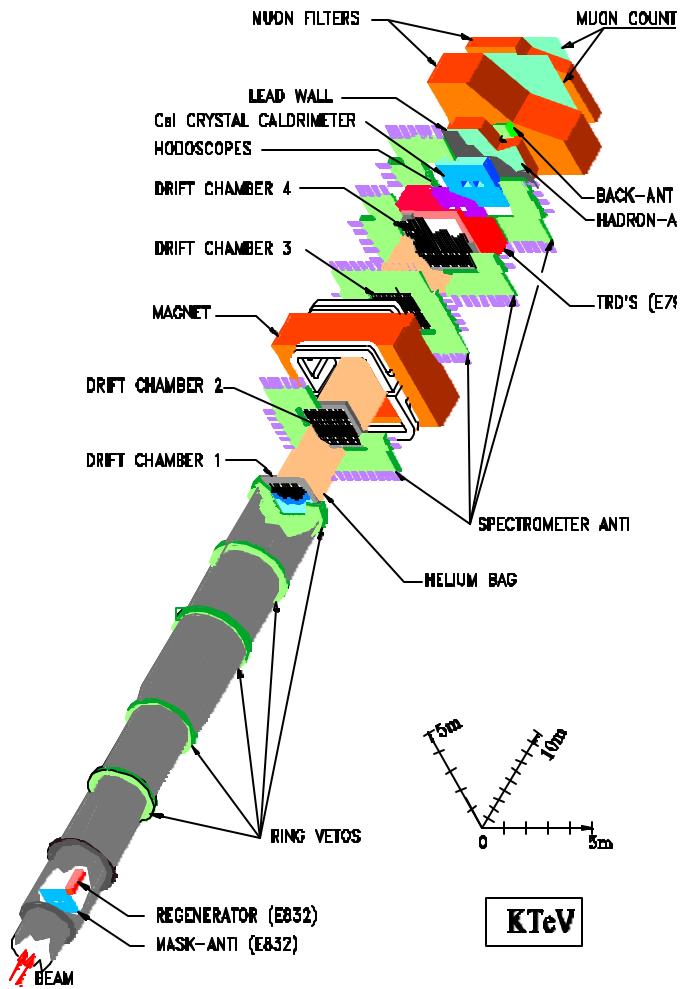


KTeV Fixed Target Run



- KTeV(E832) 96-97 Data Set: $3.3 \times 10^6 K_L \rightarrow \pi^0 \pi^0$
- KTeV (E799-II) 97 Data Set: $2.7 \times 10^{11} K_L$ Decays
- KTeV(E832) 99 Data Set: $3.7 \times 10^6 K_L \rightarrow \pi^0 \pi^0$
- KTeV (E799-II) 99 Data Set: $3.6 \times 10^{11} K_L$ Decays

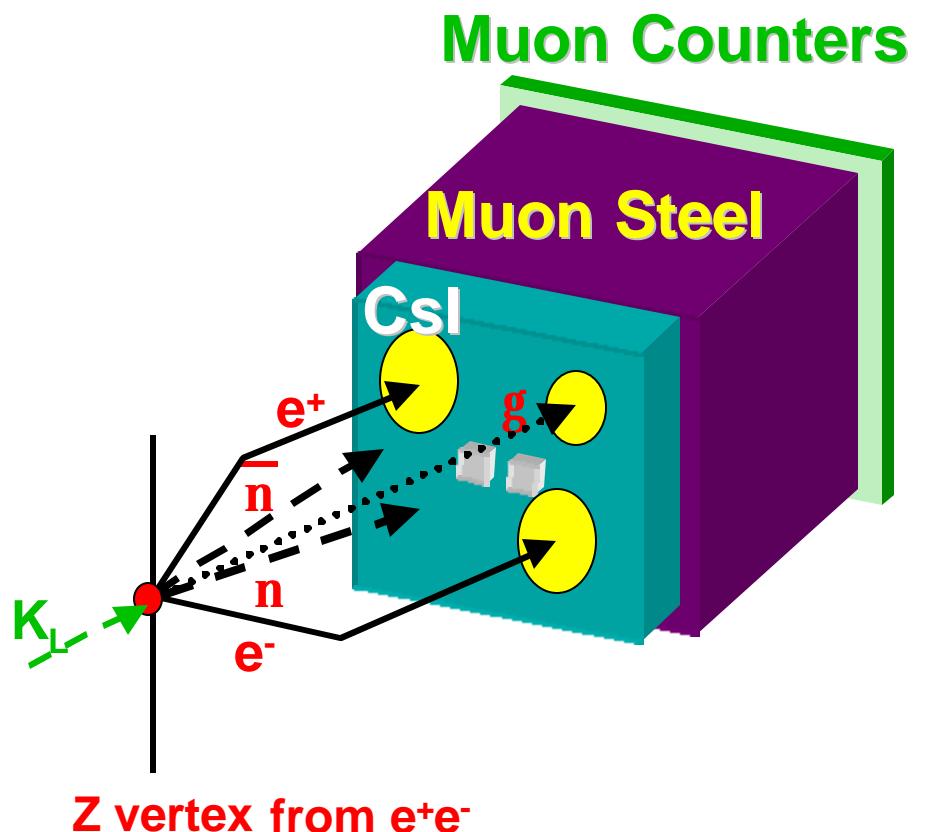
The KTeV Detector



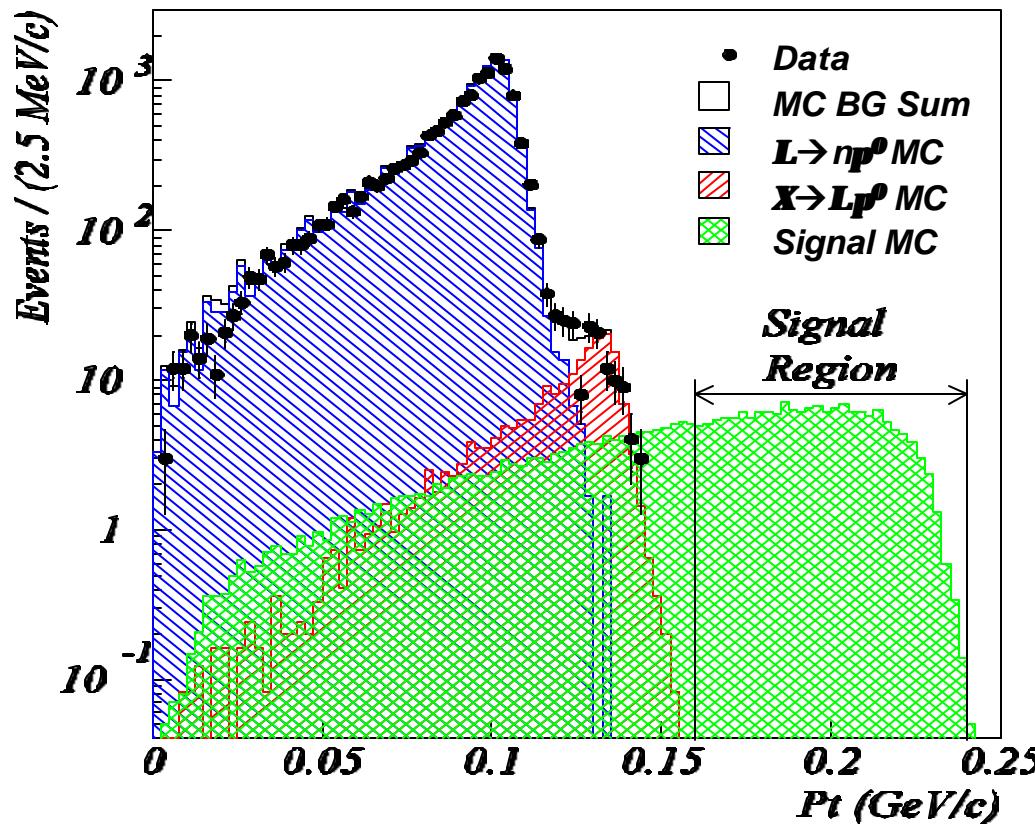
- Pure CsI Calorimeter:
(Energy resolution < 1% at $\langle E\gamma \rangle = 10\text{GeV}$, π/e rejection of > 700)
- Transition radiation detectors (p/e rejection of > 200)
- Drift chambers with resolutions ($\sim 100\mu\text{m}$)
- Clean intense beams: ($5-8)\times 10^{12}$ protons on target per spill
 - **$5-8 \times 10^9$ kaons per spill**
- KTeV (E799-II) Data Set:
6.3E11 Kaon Decays (97 + 99)

$K_L \xrightarrow{R} p^0 n \bar{n}$

- **Advantage** - Dominated by direct CP violation
- **Disadvantage** - $\pi^0 \rightarrow \gamma\gamma$ difficult; Dalitz decay BR($\pi^0 \rightarrow ee\gamma$); significant backgrounds
- 1997 Analyses
 1. Dalitz Analysis ($\pi^0 \rightarrow ee\gamma$)
 - Event Selection: 1 γ , 2 electron-like showers matched to tracks, unbalanced P_t
 - Backgrounds: $K_L \rightarrow 2\pi^0$, $K_L \rightarrow 3\pi^0$, $\Lambda \rightarrow n\pi^0$, $\Xi \rightarrow \Lambda\pi^0$
 - Normalize to $K_L \rightarrow ee\gamma$
 2. Neutral Analysis ($\pi^0 \rightarrow \gamma\gamma$)
 - Special Run - 1 Day of data taking, Single smaller beam
 - Normalize to ($K_L \rightarrow \pi^0 \pi^0$)
- 1999 Data – No Dalitz Trigger



$K_L \xrightarrow{R} p^0 n \bar{n}$



1997 Data
Dalitz Analysis

$\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 5.9 \times 10^{-7}$ ($\pi^0 \rightarrow ee\gamma$, 1997 Data) [PRD 61, 072006 (2000)]
 $\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 1.6 \times 10^{-6}$ ($\pi^0 \rightarrow \gamma\gamma$, 1997 1 Day) [PLB 447, 240 (1999)]

$K_L \xrightarrow{R} p^0 e^+ e^-$

- **Advantage:** fully reconstruct the final state.
- **Disadvantages:** not pure direct CP violation

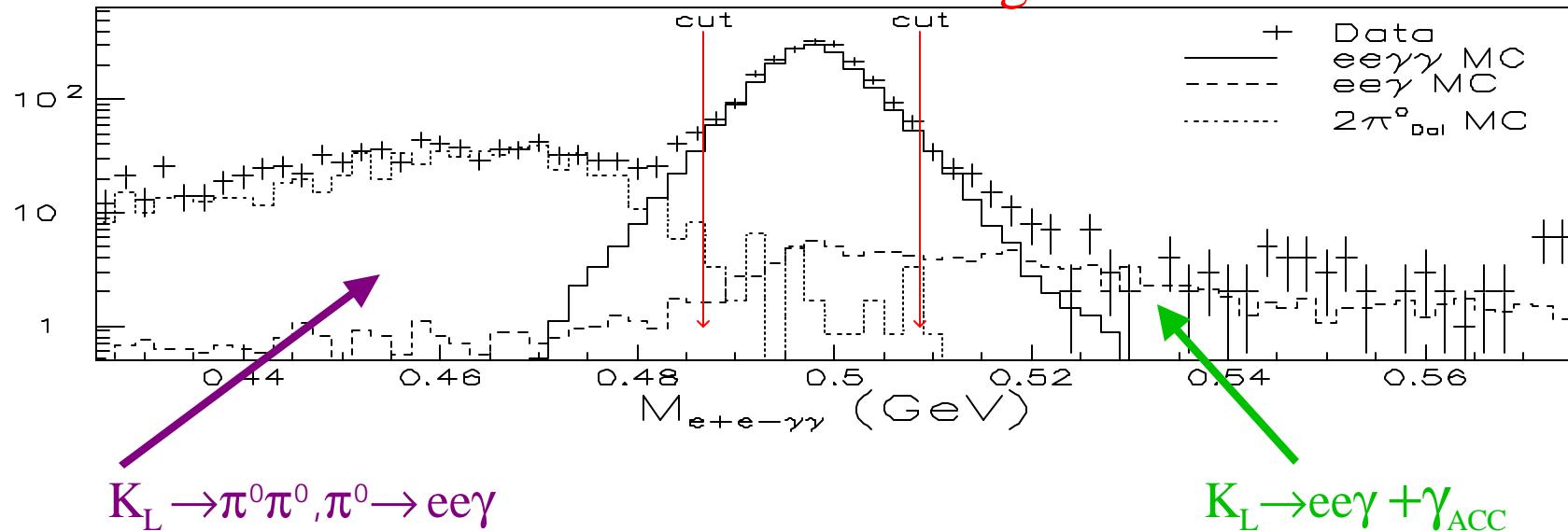
Serious background ($K_L \rightarrow ee\gamma\gamma$)

- Contributions to $BR(K_L \rightarrow \pi^0 e^+ e^-)$
 - CP Violating: $BR \sim (17 \pm 9 + 5) \times 10^{-12}$ (est. from theory+ $K_S \rightarrow \pi^0 e^+ e^-$)
 - CP Conserving: $BR \sim 0.5 \times 10^{-12}$ (est. from theory+ $K_L \rightarrow \pi^0 \gamma\gamma$)
 - Total: $BR (K_L \rightarrow \pi^0 e^+ e^-) = (1-3) \times 10^{-11}$
 - New Physics → Enhancements in BR
- Previous Result: $BR (K_L \rightarrow \pi^0 e^+ e^-) < 5.1 \times 10^{-10}$ (KTeV1997) [PRL 86, 397 (2001)]

K_L ® e⁺e⁻gg

1988 Events

76.6 ± 3.3 Est. Background

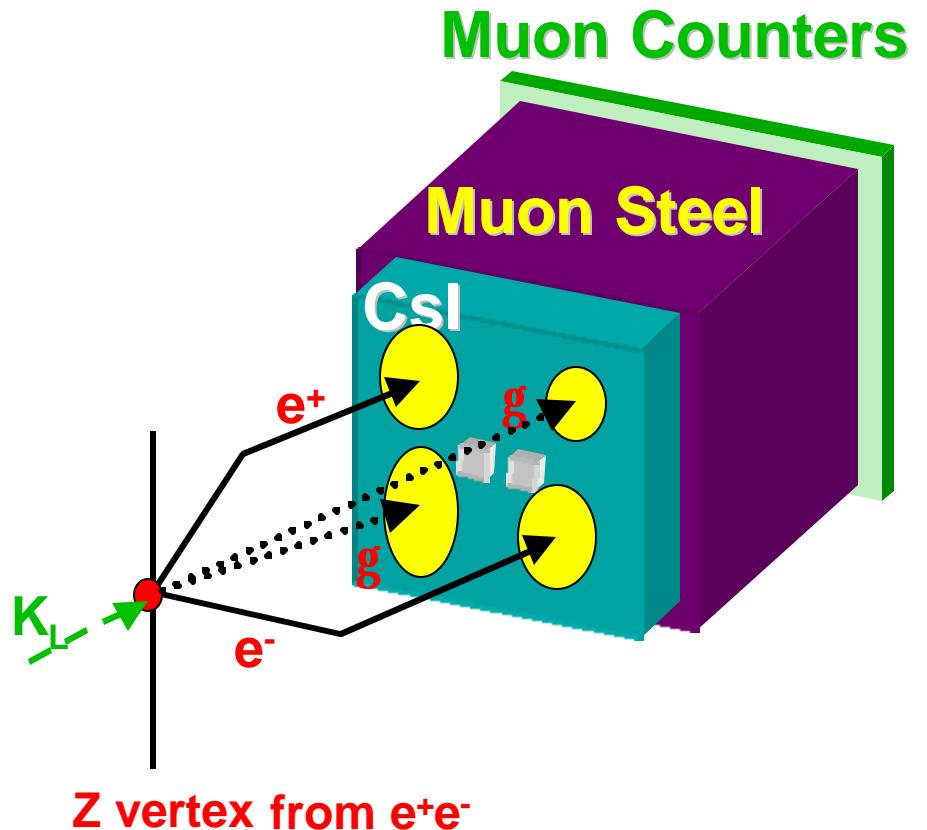


$$BR(K_L \rightarrow e^+e^-\gamma\gamma, E\gamma^* > 5\text{MeV}) = (6.31 \pm 0.14(\text{stat}) \pm 0.42(\text{sys})) \times 10^{-7} \quad [\text{PRD 64, 012003 (2001)}]$$

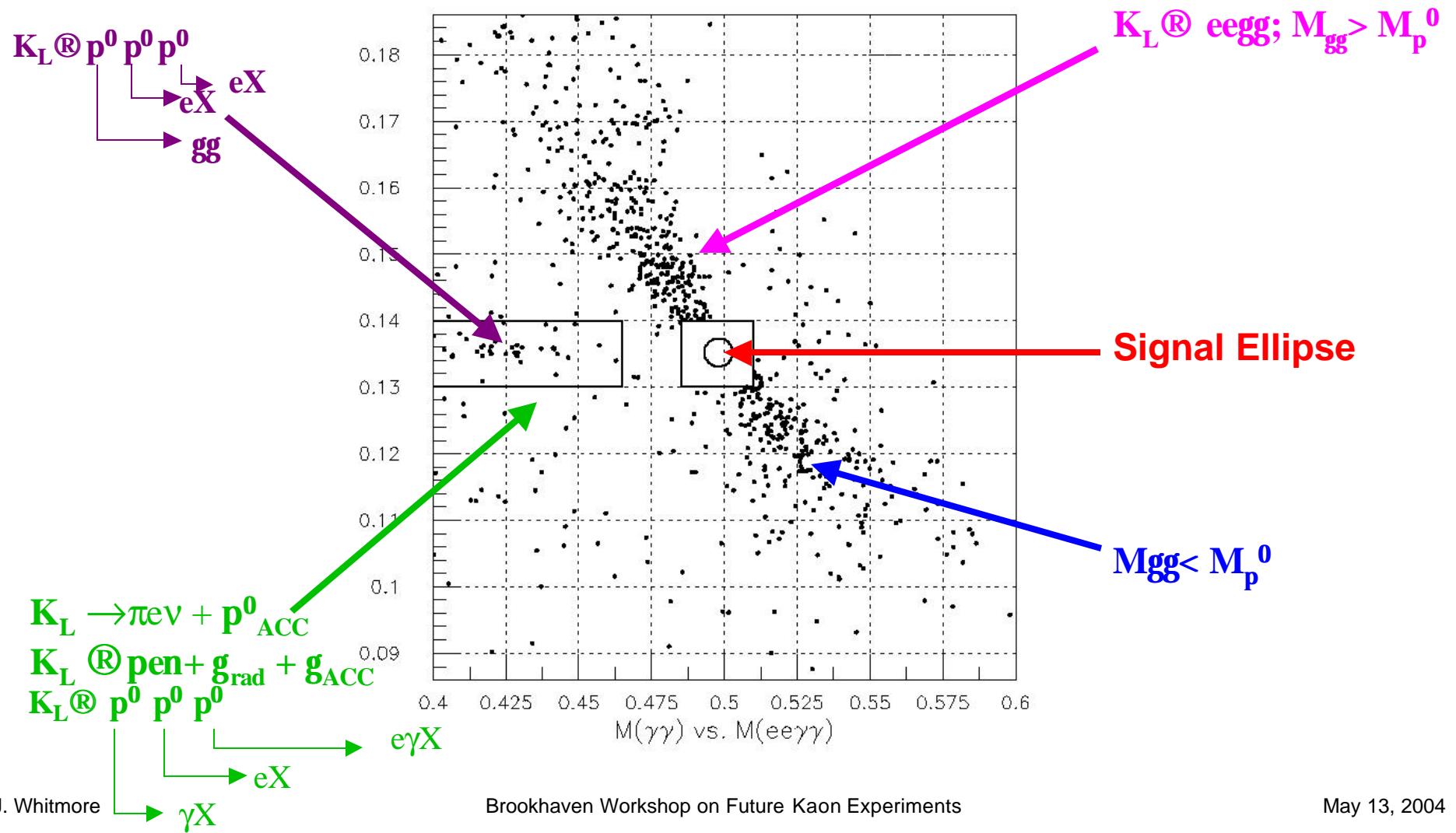
$K_L \xrightarrow{R} p^0 e^+ e^-$

- Analysis – 1999 Data

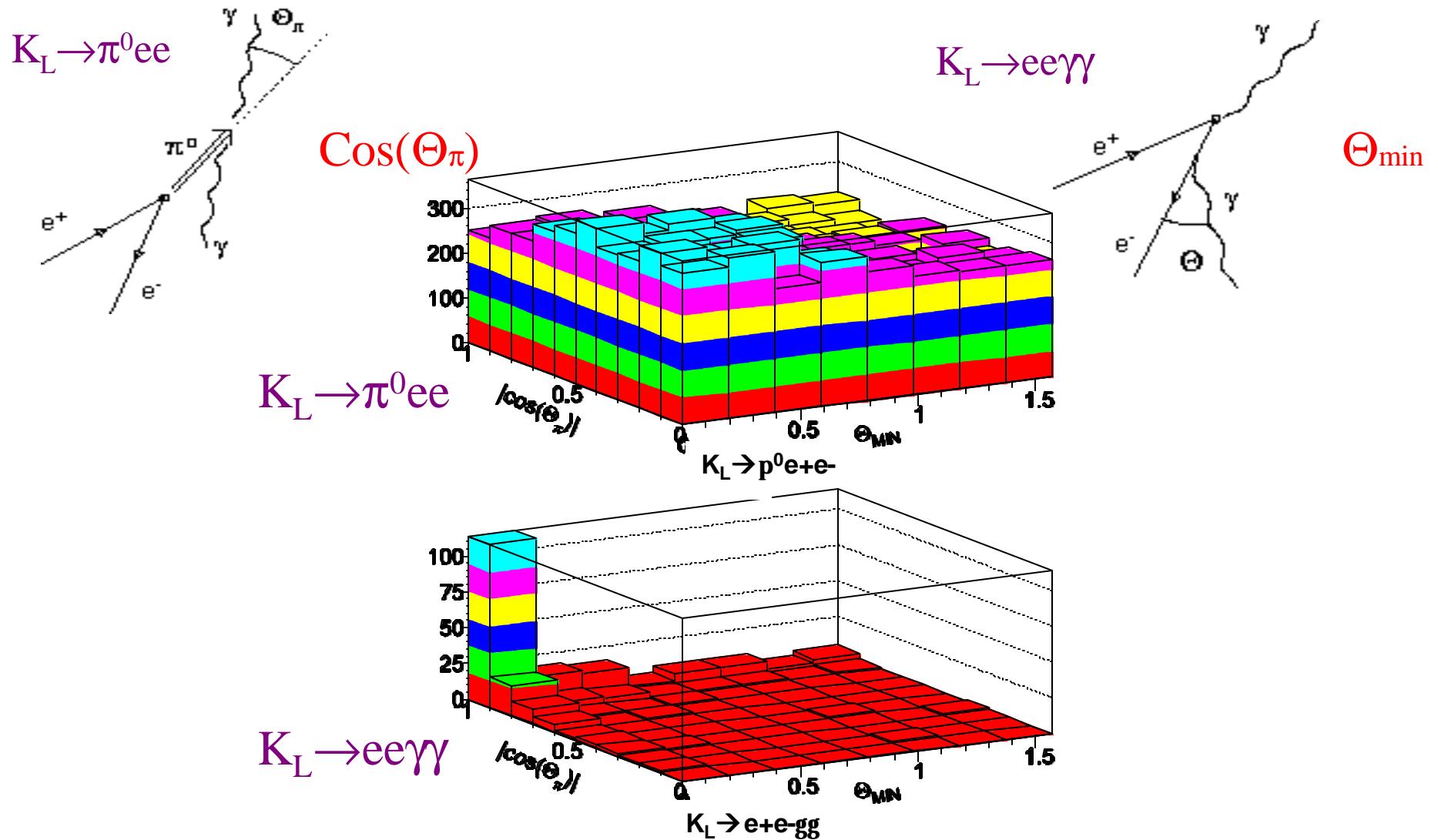
- Event selection: 2 γ forming π^0 ; 2 electron-like showers matched to tracks, CsI+TRD(π/e)
- Backgrounds: $K_L \rightarrow \pi^0 \pi^+ \pi^-$, $K_L \rightarrow \pi e \nu + \gamma_{\text{acc}} + \gamma_{\text{rad}}$, and $K_L \rightarrow ee\gamma\gamma$
 - Suppress with kinematic Cuts: $|\cos(\Theta_\pi)|$ and Θ_{\min}
 - Total contribution in the box: 3.9 ± 1.4 events (2.9 ± 0.47 events come from $K_L \rightarrow ee\gamma\gamma$)
- Normalize to $K_L \rightarrow \pi^0 \pi^0, \pi^0 \rightarrow ee\gamma$



$K_L \rightarrow p^0 e^+ e^-$



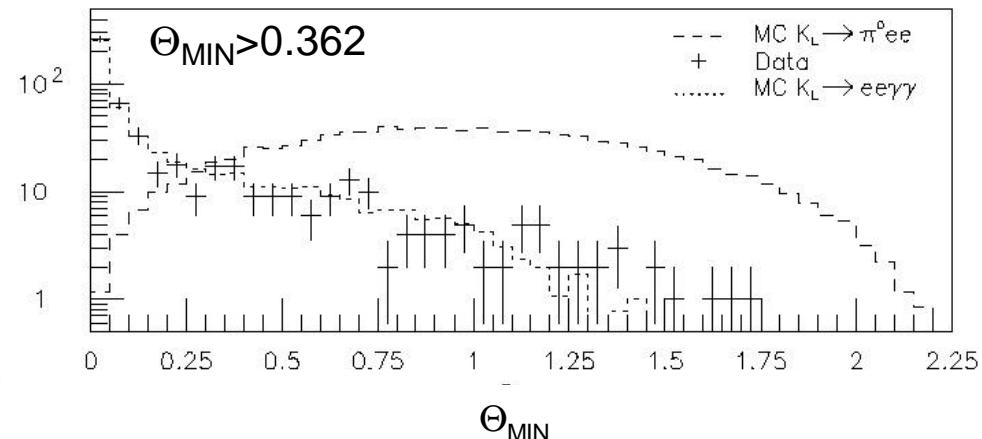
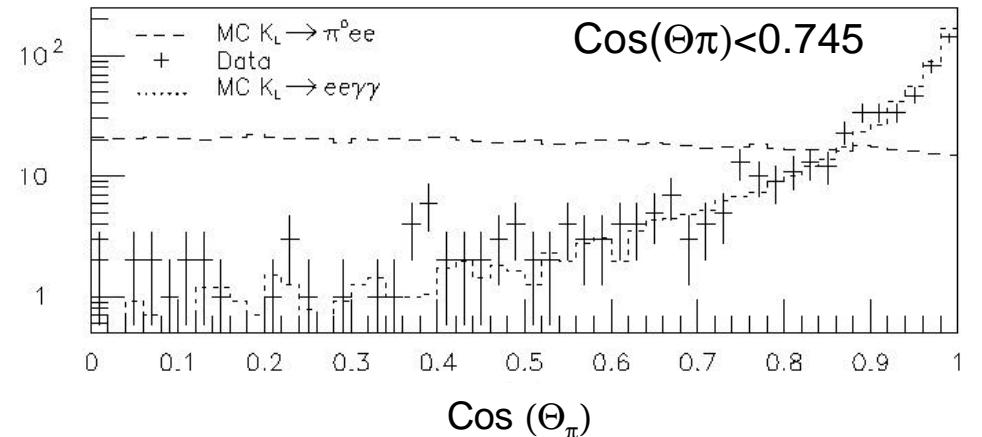
Kinematic Variables for $K_L \rightarrow p^0 e^+ e^-$ and $K_L \rightarrow e^+ e^- gg$



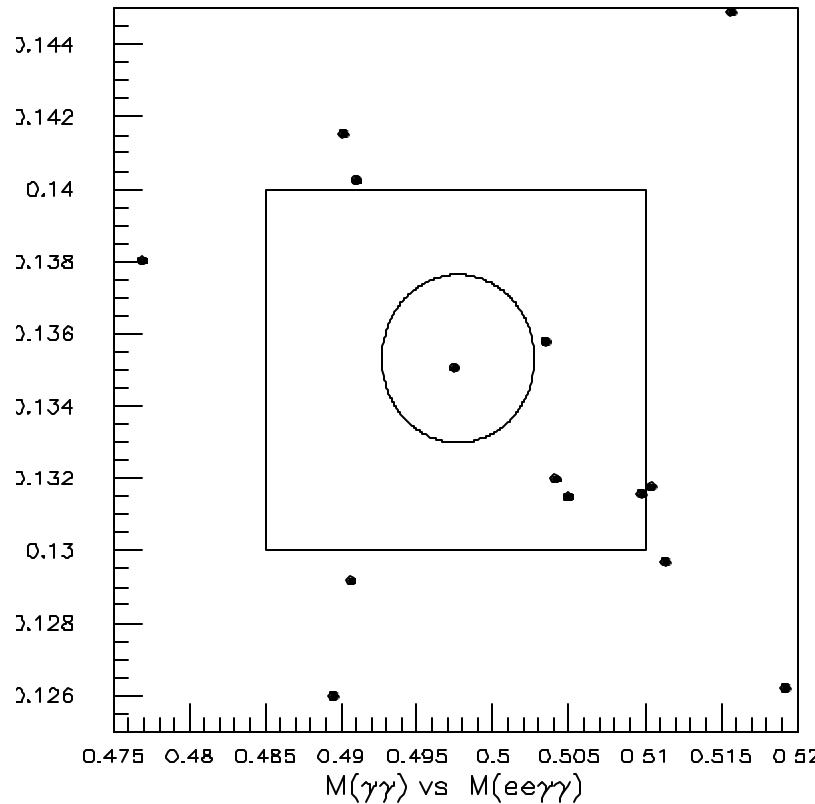
Kinematic Cuts for $K_L \rightarrow p^0 e^+ e^-$ and $K_L \rightarrow e^+ e^- gg$

- Phase space cuts optimized

- Cuts varied and expected background and signal acceptance calculated
- 90% CL BR limit determined for each set via Feldman-Cousins technique
- Assume any events are background
- Cuts optimized to yield lowest expected branching ratio limit
- Signal Acceptance: $(2.749 \pm 0.013)\%$
 - 30% less than 1997 due to accidentals (tighter TRD, phase space, and mass cuts)
- SES: 1.04×10^{-10}



$K_L \xrightarrow{R} p^0 e^+ e^-$



1999 Data

Box Region:
 $130 < mgg < 140 \text{ MeV}/c^2$
 $485 < meegg < 510 \text{ MeV}/c^2$

Signal Region:
 $\pm 2s$ in $K_L \rightarrow p^0 e^+ e^-$

Background in ellipse:
 0.99 ± 0.35

$BR(K_L \rightarrow \pi^0 e^+ e^-) < 3.50 \times 10^{-10}$ (90% C.L.) (1999) [Submitted to PRL]
 $BR(K_L \rightarrow \pi^0 e^+ e^-) < 2.8 \times 10^{-10}$ (90% C.L.) (1997+1999)

$K_L \xrightarrow{R} p^0 m^+ m^-$

- **Advantage:** Probes direct CP violation
Like $K_L \rightarrow \pi^0 e^+ e^-$ - fully reconstruct the final state
- **Disadvantages:** phase space suppression
 - Small relative to the CPC and Indirect CPV
 - Potential background ($K_L \rightarrow \mu\mu\gamma\gamma$)
- Contributions to $BR(K_L \rightarrow \pi^0 \mu^+ \mu^-)$

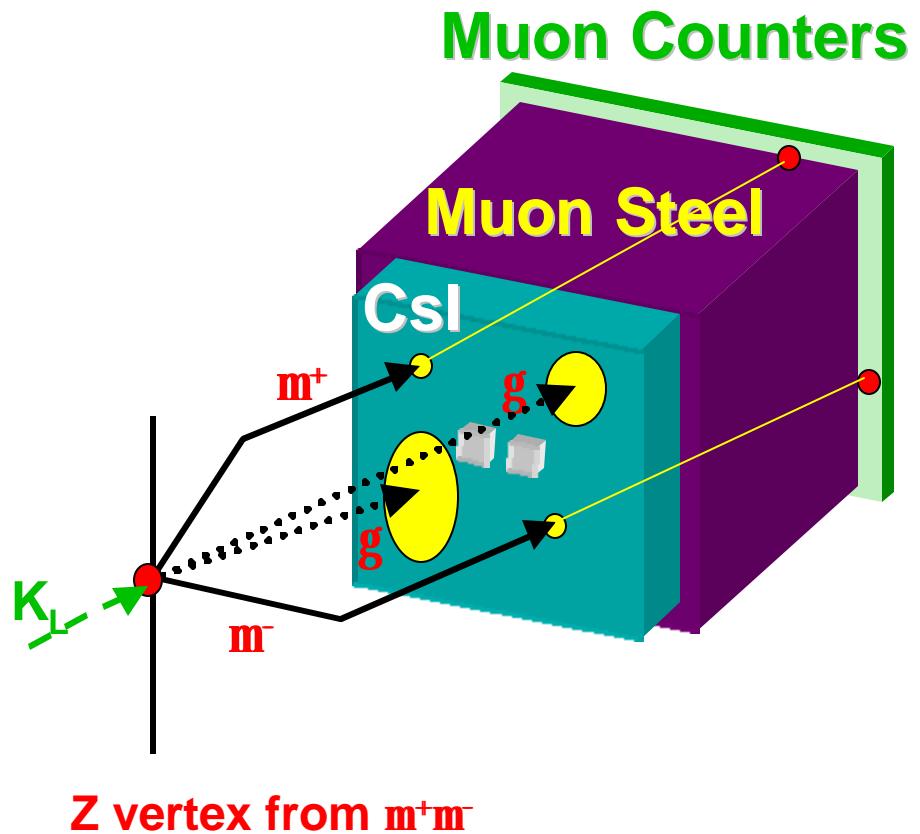
- CP Violating: $BR \sim (9 \pm 6 + 1) \times 10^{-12}$ (est. from theory + $K_s \rightarrow \pi^0 \mu^+ \mu^-$)
- CP Conserving: $BR \sim 5 \times 10^{-12}$ (est. from theory + $K_L \rightarrow \pi^0 \gamma\gamma$)
- Total: $BR(K_L \rightarrow \pi^0 \mu^+ \mu^-) = (1 - 2) \times 10^{-11}$
- New Physics → Enhancements in BR

Previous limit: $BR(K_L \rightarrow \pi^0 \mu^+ \mu^-) < 5.1 \times 10^{-9}$ (E799-I)

$K_L \xrightarrow{R} p^0 m^+ m^-$

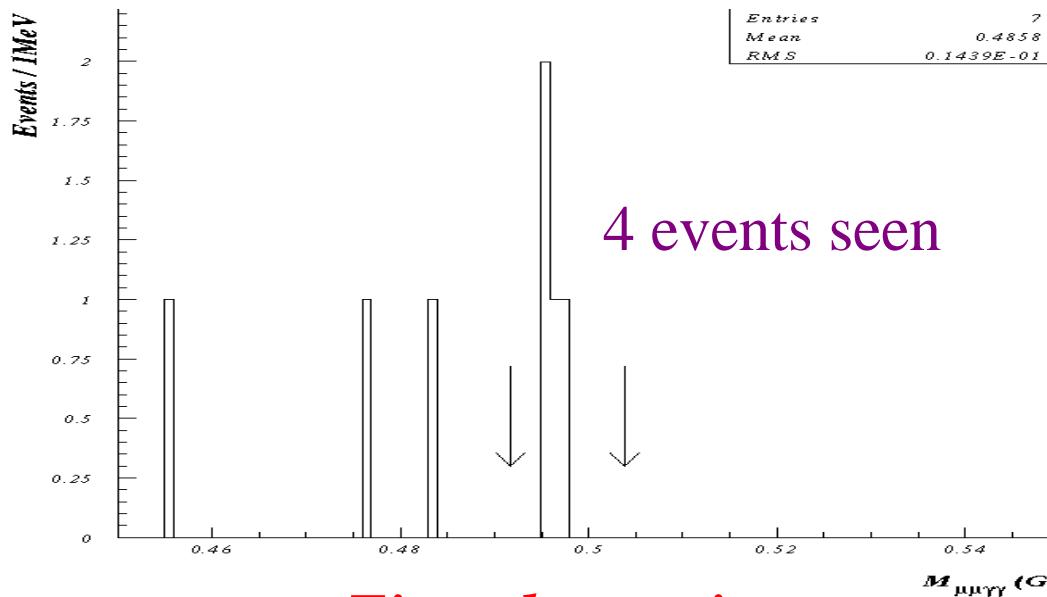
- 1997 Analysis

- Event Selection: 2 γ reconstructing as a π^0 ; 2 tracks which MIP in the calorimeter, 2 ID muons
- Backgrounds from π punch-through and π decay-in-flight from $\pi^+ \pi^- \pi^0$ and $K_L \rightarrow \pi \mu \nu$ (+ 2 γ_{ACC});
 $K_L \rightarrow \mu \mu \gamma \gamma$ (0.373 ± 0.032 evts)
 - Suppress with kinematic cuts on $M(\gamma\gamma)$ and $M(\mu\mu)$
 - Angular cuts on $|\cos(\Theta_\pi)|$ and Θ_{\min} less effective than with $e e \gamma \gamma$
 - Total contribution: 0.87 ± 0.15 events
 - Normalize to $\pi^+ \pi^- \pi^0$ decays



- Dangerous background for $K_L \rightarrow \pi^0 \mu^+ \mu^-$
- Never been observed
- Analysis
 - Event Selection: 2 γ which do not reconstruct as a π^0 ;
2 tracks which MIP in the calorimeter, 2 ID muons
 - Backgrounds from $K_L \rightarrow \pi \mu \nu (+2\gamma_{\text{ACC}})$, $\mu \mu \gamma + \gamma_{\text{ACC}}$
 - Kinematic Cuts: $E\gamma$
 - Total Contribution: 0.155 ± 0.081
 - Normalize to $K_L \rightarrow \pi^+ \pi^- \pi^0$
- QED Pred: $\text{BR}(K_L \rightarrow \mu^+ \mu^- \gamma \gamma) = (9.1 \pm 0.78) \times 10^{-9}$

K_L ® mmgg_{oo}

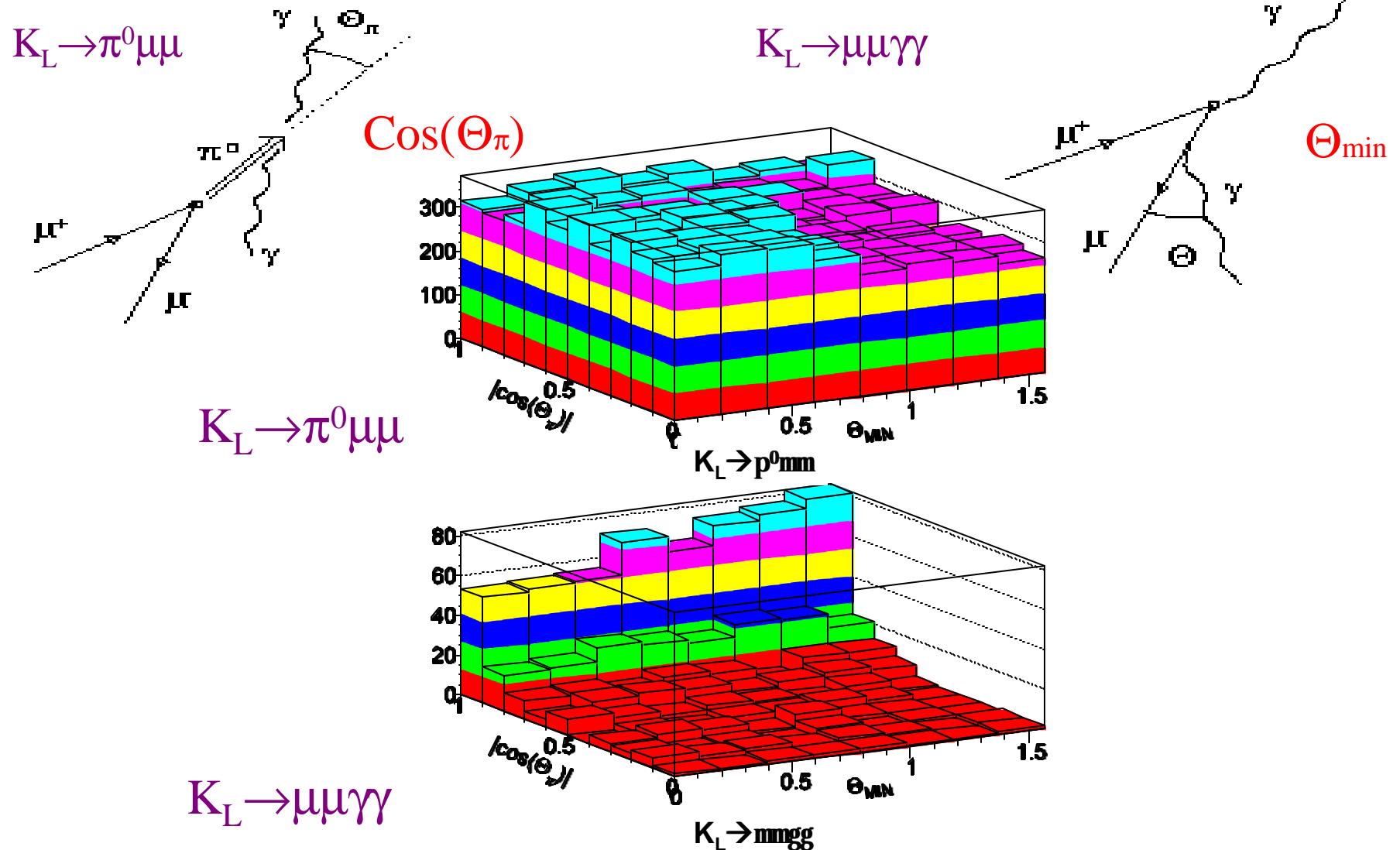


$$\text{BR}(K_L \rightarrow \mu^+ \mu^- \gamma\gamma, M\gamma\gamma \geq 1 \text{ MeV}/c^2) = \\ (10 \pm 4 \stackrel{+7}{-5} \text{ (stat)} \pm 0.7 \text{ (sys)}) \times 10^{-9}$$

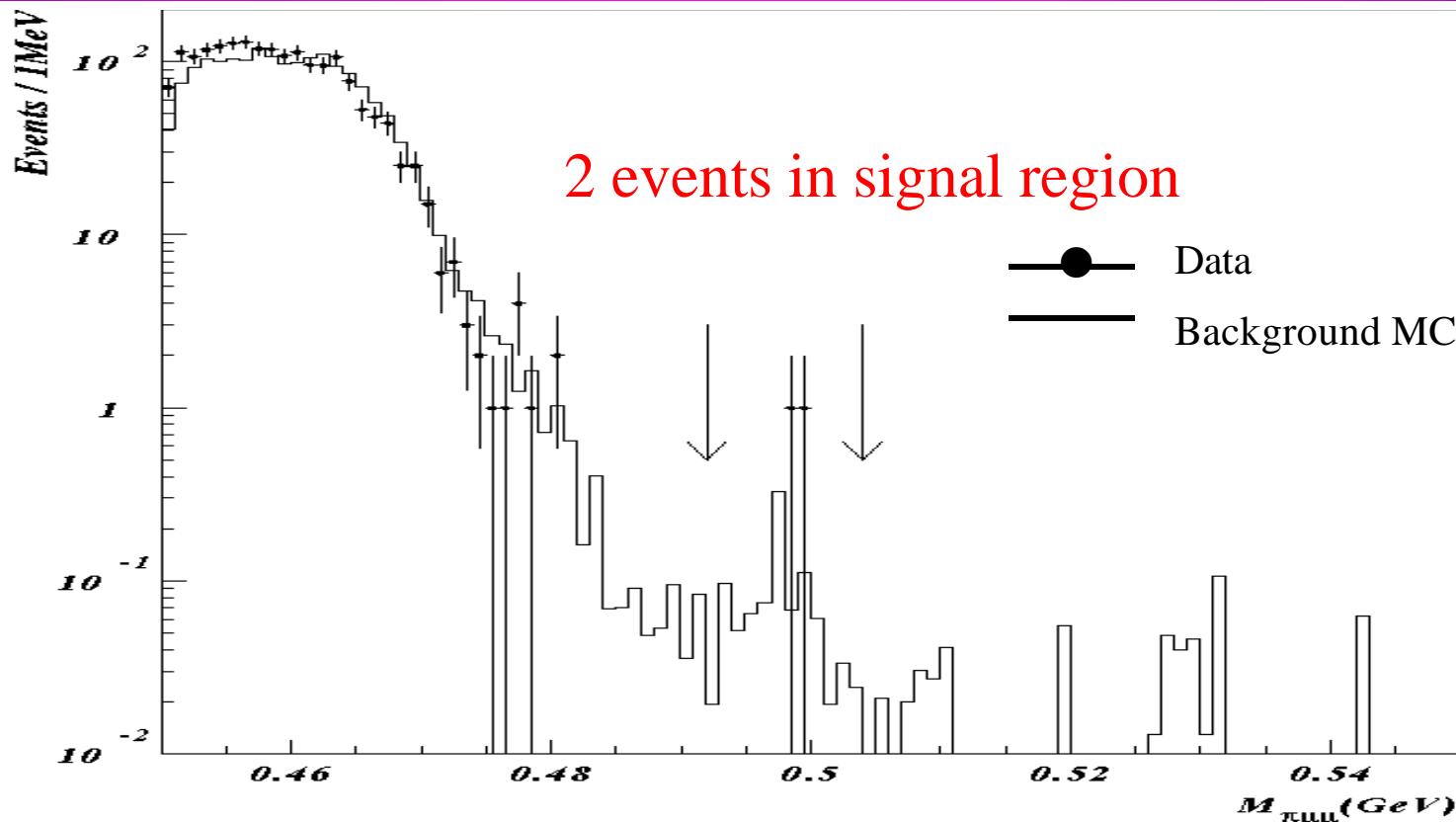
$$\text{BR}(K_L \rightarrow \mu^+ \mu^- \gamma\gamma, E\gamma^* \geq 10 \text{ MeV}) = \\ (1.42 \stackrel{+1.0}{-0.8} \text{ (stat)} \pm 0.10 \text{ (sys)}) \times 10^{-9}$$

[PRD 62, 112001 (2000)]

Kinematic Distributions for $K_L \rightarrow p^0 m^+ m^-$ and $K_L \rightarrow m^+ m^- gg$



$K_L \xrightarrow{R} p^0 \mu\mu$



$\text{BR}(K_L \rightarrow \pi^0 \mu\mu) < 3.8 \times 10^{-10}$ (90% C.L.) [PRL 86, 5425 (2001)]

Summary

- Analyzed 1997 data - $\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 5.9 \times 10^{-7}$ ($\pi^0 \rightarrow e e \gamma$)
 - $B(K_L \rightarrow e^+ e^- \gamma\gamma) = (6.31 \pm 0.14(\text{stat}) \pm 0.42(\text{sys})) \times 10^{-7}$
 - No Dalitz trigger in 1999 data
 - Look forward to future experiments – KOPIO and E391a
- Analyzed full KTeV data set (1997 + 1999) - $\text{BR}(K_L \rightarrow \pi^0 e^+ e^-) < 2.8 \times 10^{-10}$ (90% C.L.)
- Analyzed 1997 data - $\text{BR}(K_L \rightarrow \pi^0 \mu \bar{\mu}) < 3.8 \times 10^{-10}$ (90% C.L.)
 - $B(K_L \rightarrow \mu^+ \mu^- \gamma\gamma) = (1.42 (+1.0 - 0.08) \pm 0.10) \times 10^{-9}$
 - Currently analyzing 1999 data
 - Combined 1997+1999 data set $\sim 2 \times 1997$
 - More accidentals – tighter cuts (lose acceptance)
 - Normalize to $K_L \rightarrow \mu^+ \mu^- \gamma$ – reduce uncertainties from muon system
 - Expected SES (1997+1999) $\sim 1 \times 10^{-10}$